Impact Assessment of High Penetrations of Grid-connected Photovoltaic (PV) System on the Low Voltage Distribution Network

Salem Ali, Nicola Pearsall and Ghanim Putrus
School of Computing, Engineering and Information Sciences
Northumbria University, Newcastle upon Tyne, UK
Email: ali.salem@unn.ac.uk

Abstract

In recent years, the use of photovoltaic (PV) systems as an integral part of building facades or roofs has become one of the fastest growing markets worldwide. Therefore, grid-connected photovoltaic (GCPV) systems could have great potential to supply part of the consumer's own power demand. However, when the house or business requires less power than the PV system is generating, the surplus power will be fed back to the grid. Because the existing distribution networks are not designed and constructed to accommodate high penetration of distributed energy systems, it is possible to have reverse power flow and increase the steady-state voltage level on feeder lines especially during periods of low load demand and high generation. This paper assesses the effect of high penetration levels of small-scale grid-connected PV systems on the voltage quality of the UK low voltage distribution network feeders. The worst case scenario of high penetration of grid-connected PV systems with a typical daily summer load profile is considered to estimate the amount of voltage variation on distribution network feeders. The power system dynamic program MATLAB is used to carry out this assessment.

Key words

Distribution network, PV system, power quality, voltage rise

Introduction

Recently, renewable energy sources such as wind, photovoltaic (PV) and geothermal have received more attention as alternative means of generating electricity. In particular, installation of grid-connected photovoltaic (GCPV) systems on rooftop of the houses and commercial buildings has become one of the fastest growing markets worldwide. This increase is due to the cost reduction of PV panels and technical progress in power electronic conversion and semiconductor devices which are convenient for local generation [1]. In addition, grid-connected PV systems have many economic as well as environmental advantages such as allowing flexibility in system design, being simple to install in any area where the solar irradiation is available, being non-polluting, requiring little maintenance and emitting no noise due to the absence of moving parts [2, 3]. Therefore, grid-connected PV systems could have great potential to supply part of the consumer's owner demand and offer significant benefits in terms of reduced energy bills by feeding any surplus power into the grid when the PV generation exceed the household demand [4, 5].

However, because the existing low voltage distribution has been designed and operated under the basis that power flows from higher to lower voltage levels, integrating a high penetration level of grid-connected PV systems into the low voltage distribution network (LVDN) could cause operational problems. One of the technical issues is a possible voltage rise along distribution feeders as a result of reverse power flow, especially at low demand and high generation conditions. Any overvoltage issue could affect household appliances and lead to other technical challenges such as safety and protection problems in the network, especially if other types of distributed generation such as small-scale wind turbines are also integrated into the grid[6].

In the UK the use of grid-connected PV systems on buildings has grown over the last few years with many impressive examples already in operation. Generally, the rated output of a typical domestic grid-connected PV system is in the region of a few (1-5) kW[7]. During the day PV output power will be consumed within the building when there is active load and any excess will be injected into the public grid. Feeding power to the grid could happen during the hours of daylight when the generated power is higher than the load demand due to a high solar irradiation level, especially in sunny weather conditions (summer season). Figure 1 shows a typical daily load profile [8] and the output power of 3 kW PV system on a clear summer day in the UK. The summer load profile is considered as it provides a good example of when there may be more energy being produced by the PV than is consumed by the local load across the middle of the day. In this paper, the Matlab/Simulink package is used to investigate the occurrence of overvoltage due to a high penetration level of grid-connected PV systems on the UK low voltage distribution network feeders (11/0.4 kV).

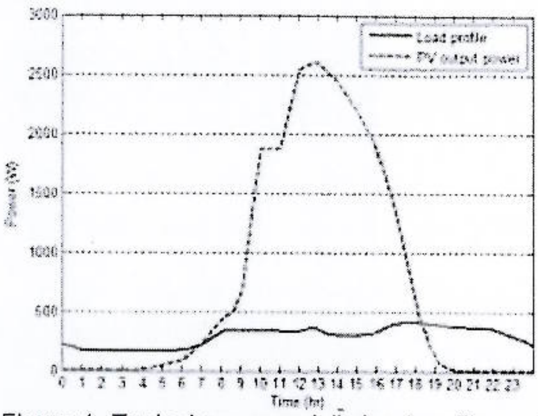

Figure.1. Typical summer daily load profile and PV output power

Network modelling

A. Distribution network model

To assess the impact of different penetration levels of grid-connected PV systems, actual data for both the network and a typical house load profile have been used to build a realistic model. This network is fed at a primary 500 MVA substation which consists of two 33/11 kV 20 MVA transformers to supply six 11 kV outgoing feeders, with each feeder supplying eight 11/0.4 kV substations. Each 11/0.4 kV substation supplies 384 properties which are distributed along four outgoing radial feeders. In total, the network supplies 18,432 properties. In order to simplify the analysis, only one 400 V feeder together with its connected loads and GCPV systems was modelled in detail whilst the rest were simplified as a lumped load. Figure 2 presents a schematic diagram of this network.

B. Simulink network model

The Matlab/Simulink and Power System Block-set is used to develop and simulate the distribution network. In order to simplify the model, five 11 kV feeders are assumed as one lumped load. One 11 kV feeder is modelled in details and houses are assumed to be distributed along the line in eight feeders, seven feeders are modelled as one lumped load whereas one 11/0.4 kV feeder with loads and the grid-connected PV systems is modelled in details as illustrated in Figures 3. Each house was assumed to have a PV system. All the feeders are underground cables only and each 400 V feeder is supplying 384 houses.

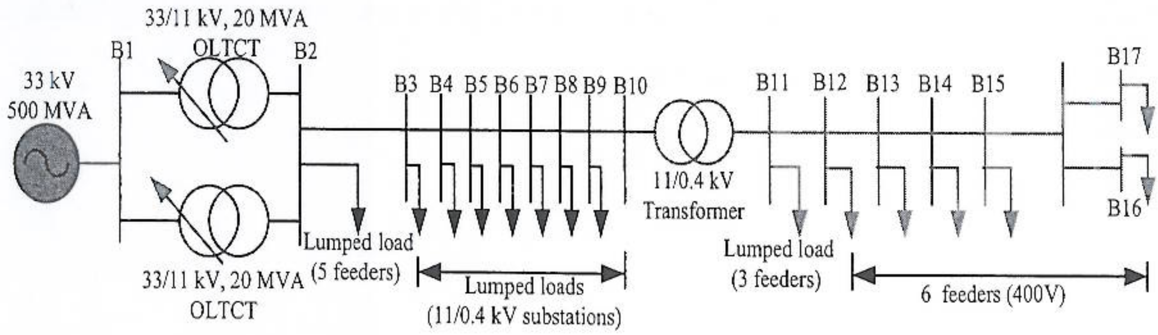

Figure.2. Typical distribution network model

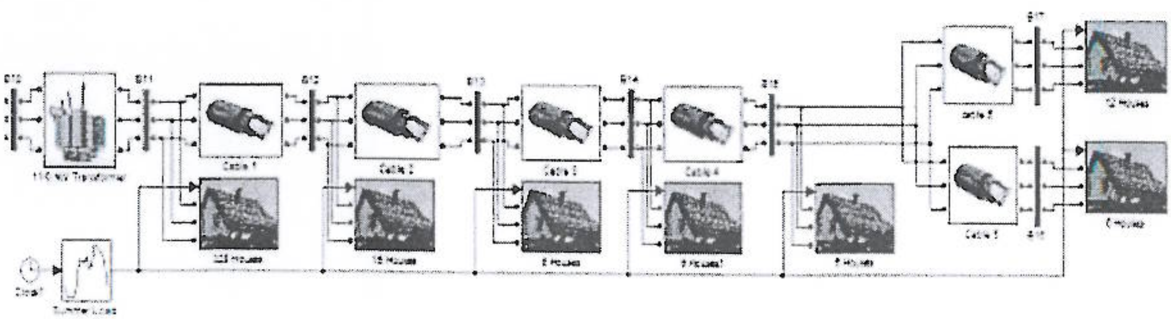

Figure.3. Detailed 400 V feeder with loads and PV systems

Simulation results and analysis

The network model was simulated with the variation of a typical daily load profile over 24 hours with and without PV systems. The voltage at each node along the 400 V feeder (B11 to B17) was measured and the voltage profile is presented in Figure 4. The voltage profile indicates that the voltage level remains within the statutory limits (+1.1 and -0.94 p.u.) of the nominal voltage (400 V), with the lowest voltage happening at 5 p.m. when most of the people return home.

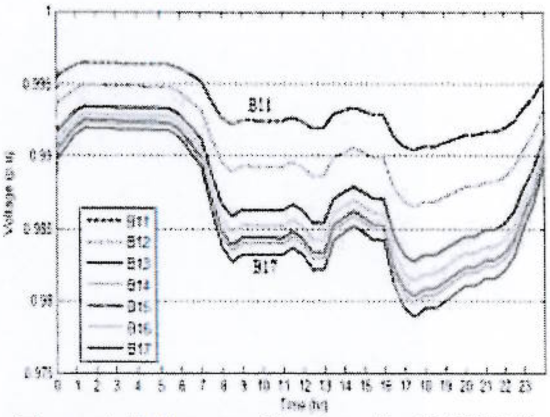

Figure.4. Voltage profile along the 230/400 V feeder without PV systems

In the second part, the network was simulated with the same typical summer load profile and different scenarios of PV penetration levels. In the first scenario, a 25% penetration level of GCPV systems is considered (that is, 25% of the houses have GCPV systems) and the voltage profile along the 230/400 V feeder (B11 to B17) is determined and presented in Figure 5. The voltage profile indicates that under these conditions, the voltage level remains within the statutory limits (+1.1 and -0.94 p.u) of the nominal voltage 230/400 V.

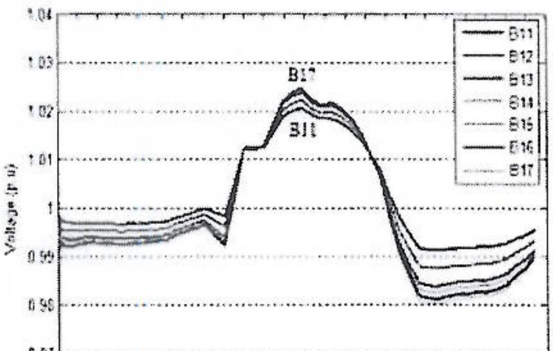

Figure.5. Voltage profile along the 230/400 V feeder with 25% PV penetration level

In the second scenario, the network was simulated with 50% and 100% penetration levels and the node voltages are determined, as before, and presented in Figures 6 and 7, respectively.

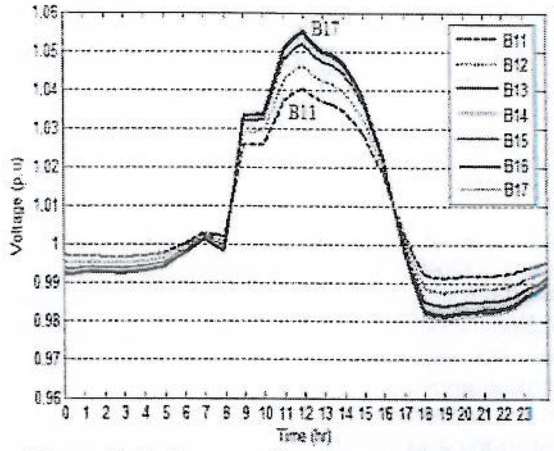

Figure.6. Voltage profile along the 230/400 V feeder with 50% PV penetration level

Figure 7 shows that, when the PV penetration level was increased to 50% the voltage level along the feeder is still within the statutory limits (+1.1 and -0.94 p.u). In the third scenario, the penetration level is increased to 100% which is the worst case condition since it assumes maximum penetration of PV (every house has an installed PV system). The results of this scenario indicated that the voltage level along the 230/400 V feeder increases above the statutory limits of the nominal voltage 230/400 V in the time between 11 a.m. and 2 p.m. (midday where load is expected to be low and PV generation is high), whereas the voltage level at the beginning of the feeder (B11 and B12) remained just under the statutory limits.

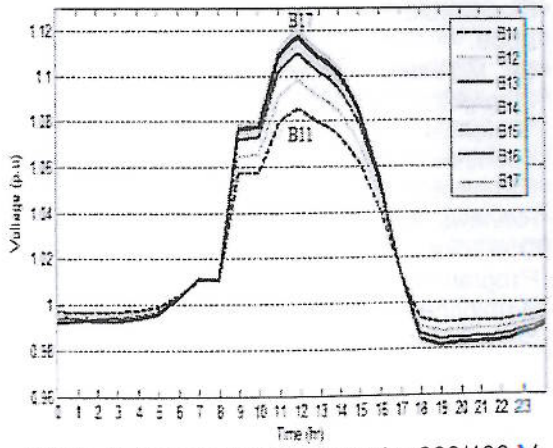

Figure.7. Voltage profile along the 230/400 V feeder with 100% PV penetration level

Conclusions

In this paper, a dynamic model of a typical UK low voltage distribution network with different penetration level of grid-connected PV systems has been developed and simulated using MATLAB/Simulink. This model is being used to investigate the impact of high penetration levels of grid-connected PV systems on the voltage quality of the UK residential low voltage distribution network. The key results that are derived from the simulation study show that, under certain conditions, GCPV systems can affect the voltage quality of the network. This impact becomes more significant with higher solar irradiation level and low demand conditions, as would be expected in summer season. Therefore, proper voltage control, for example implementing storage systems or restructuring the network may be necessary in order to accommodate a high penetration of PV systems and other types of distributed generation such as micro wind turbines. In this context, future work will extend the analysis to investigate the voltage profile of the network with the integration of electric vehicles (EV) as storage system to optimise the provision of power from PV systems and support the network (supply/demand matching).

References

[1] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," in Industry Applications, IEEE Transactions on. vol. 41, pp. 1292-1306. 2005.

[2] F. Almonacid, C. Rus, P. Perez, and L. Hontoria, "Estimation of the energy of a PV generator using artificial neural network," Renewable Energy, vol. 34, pp. 2743-2750. 2009.

[3] G. Makrides, B. Zinsser, M. Norton, G. Georghiou, M. Schubert, and J. Werner, "Potential of photovoltaic systems in countries with high solar irradiation," Renewable and Sustainable Energy Reviews, vol. 14, pp. 754-762. 2010.

[4] D. Toke, "Making the UK Renewables Programme FITTER" University of Birmingham, World Future Council (UK Office) 2007.

[5] M. Mendonca, "The UK Feed-In Tariff: A user Survey," Birkbeck Institute of Environment, Birkbeck College, University of London, 2011.

[6] T. Yun Tiam and D. S. Kirschen, "Impact on the Power System of a Large Penetration of Photovoltaic Generation," in Power Engineering Society General Meeting, 2007. IEEE, pp. 1-8.

[7] J. Hernandez, A. Medina, and F. Jurado, "Impact comparison of PV system integration into rural and urban feeders," Energy Conversion and Management. Vol. 49, pp.1747-1765. 2008

[8] C. Barbier, A. Maloyd, and G. Putrus, "Embedded Controller for LV Network with Distributed Generation," DTI project, URN number: 07/921. Contract number: K/EL/00334/00/00, UK, 2007.